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ANALYSIS OF STIMULATED ELECTRON RADIATION.(U)  
MAR 79 J SOLN, R L WILLIAMS  
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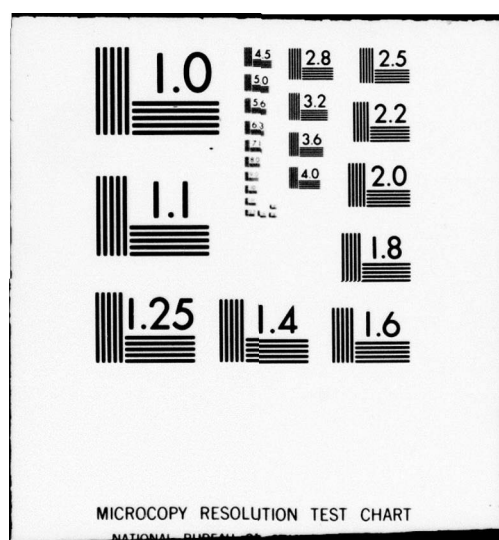
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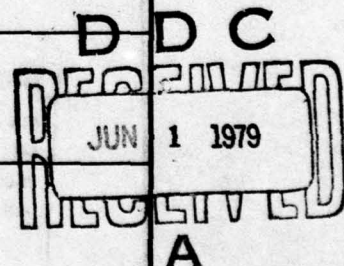
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and frequency upshifts as functions of a solid angle for the vacuum and forward and backward Cerenkov branches. The total radiated powers also were evaluated.

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## 1. INTRODUCTION

A theory dealing with stimulated radiation in a medium, due to the interaction between an electron beam and a coherent electromagnetic field, has been formulated recently by using the formalism of partial differential equations with respect to coupling constants (PDECC).<sup>1</sup>

In this report, we analyze the stimulated radiation in the light of this theory, with the emphasis on experiments yet to be carried out. In doing so, we have extended some of the results from reference 1 by arriving at, in addition to the power spectrum, expressions for radiated power, the number of photons per unit frequency, and the frequency upshifts, all as functions of solid angle. All these quantities were calculated separately for the vacuum and forward and backward Cerenkov branches. The total radiated power also was evaluated, and an interesting sum rule was derived that may prove to be very useful to experimentalists.

In section 2, we briefly review the theory for stimulated radiation in a medium,<sup>1</sup> together with newly derived general expressions for the radiated power and the number of photons per unit frequency interval, all as functions of solid angle.

Section 3 is devoted to specific expressions for stimulated electron radiation. First, the expression for the decay rate,  $\Gamma$ , is given. From  $\Gamma$ , we deduce specific expressions for the frequency upshifts, the radiated power, and the number of photons per unit frequency, all as functions of solid angle. Here, the total radiated power in the vacuum branch and the sum rule for the total radiated powers in Cerenkov branches are given.

The numerical analysis of the radiated power, the frequency upshifts, and the number of photons per unit frequency as functions of solid angle is given section 4. There, the results are discussed and summarized.

For convenience, we assume an infinite medium of unit magnetic permeability ( $\mu = 1$ ), so that the index of refraction,  $n$ , and the real dielectric constant,  $\epsilon$ , are related by  $n^2 = \epsilon$ . In addition to using the rationalized Heaviside's system of units, we also set velocity of light  $c = 1$ . In the specific example, we show how our results can be expressed in cgs units.

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<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, Phys. Rev. D, 6 (1978), 2140.

## 2. REVIEW OF AND SOME REMARKS ON STIMULATED RADIATION

An older approach to stimulated radiation (resulting from interaction between electrons and an incident electromagnetic field), as well as to synchrotron and Cerenkov radiation characteristics, is to calculate explicitly the radiation electromagnetic fields, from which the radiation characteristics are then determined from the asymptotic forms of the Poynting vector.

Here, we present another method, whose origin is in the formalism of partial differential equations with respect to coupling constants (PDECC),<sup>1-3</sup> which is compact in its formulation. Basically, all that is needed is the vacuum excitation amplitude<sup>1</sup>

$$\langle 0|S|0\rangle = \exp \left\{ -\frac{i}{2(2\pi)^4} \int d^4k \tilde{J}^\mu(-k) \tilde{D}_{\mu\nu}^{(+)}(k) \tilde{J}^\nu(k) \right\}, \quad (1)$$

where  $S$  denotes the S-matrix. In equation (1),  $\tilde{J}^\mu(k)$  is the Fourier transform of a conserved classical current  $J^\mu(x)$ , defined as

$$\tilde{J}^\mu(k) = \int d^4x e^{-ikx} J^\mu(x), \quad (2)$$

and  $\tilde{D}_{\mu\nu}^{(+)}(k)$  is the Fourier transform of the positive frequency singular function, which for a medium at rest becomes<sup>1</sup>

$$\tilde{D}_{\mu\nu}^{(+)}(k) \rightarrow \tilde{D}_{ij}^{(+)}(k) = -2\pi i \epsilon_{ij}(k) \frac{\theta(k^4)}{2|\vec{k}|} \delta(|\vec{k}| - nk^4),$$

$$\epsilon_{ij}(k) = \delta_{ij} - \frac{\hat{k}_i \hat{k}_j}{1}. \quad (3)$$

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, Phys. Rev. D, 6 (1978), 2140.

<sup>2</sup>J. Soln, *Partial Differential Equations with Respect to Coupling Constants: Electromagnetic Mass Difference of Hadrons*, Phys. Rev. D, 6 (1972), 2277.

<sup>3</sup>J. Soln, *Covariant Perturbation Theory for Chiral Lagrangians*, Phys. Rev. D, 7 (1973), 1637.



This formulation is quantum mechanical (we have also set  $\hbar = 1$  in our system of units). The vacuum excitation amplitude is exactly the same as what Schwinger et al<sup>4</sup> call the vacuum persistence amplitude in the language of source theory.

The decay rate,  $\Gamma(t)$ , is determined from the vacuum excitation probability through

$$|\langle 0|S|0\rangle|^2 = \exp \left\{ -\int dt \Gamma(t) \right\}, \quad (4)$$

which, when combined with equation (1), gives<sup>1</sup>

$$\int dt \Gamma(t) = \frac{i}{(2\pi)^4} \int d^4k \tilde{J}_\mu(-k) \tilde{D}_{(+)}^{\mu\nu}(k) \tilde{J}_\nu(k). \quad (5)$$

Equation (5) is our main relation. From it, we evaluate the radiated power and the number of photons per unit frequency as functions of solid angle. In our applications,  $\Gamma(t)$  is actually independent of time. To see specifically what happens in this case, we write

$$\Gamma(t) = \frac{1}{2\pi} \int d\omega e^{-i\omega t} \tilde{\Gamma}(\omega),$$

where, for  $\Gamma$  independent of  $t$ ,

$$\tilde{\Gamma}(\omega) = \Gamma 2\pi \delta(\omega),$$

giving

$$\int dt \Gamma(t) = \tilde{\Gamma}(0) = \Gamma 2\pi \delta(0). \quad (6)$$

When this is substituted into equation (5), we get

$$\Gamma \delta(0) = \frac{i}{(2\pi)^5} \int d^4k \tilde{J}_\mu(-k) \tilde{D}_{(+)}^{\mu\nu}(k) \tilde{J}_\nu(k). \quad (7)$$

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, Phys. Rev. D, 6 (1978), 2140.

<sup>4</sup>J. Schwinger, Wu-Yang Tsai, and T. Erber, *Classical and Quantum Theory of Synergic Synchrotron-Cerenkov Radiation*, Ann. Phys., 96 (1976), 303.

The delta function at the origin drops out in calculations since it is implicitly present on the right side of equation (7).

In a semiclassical theory of radiation, the emission of photons of any momenta and polarizations occurs in a statistically independent way. Thus, the total probability,  $W_m$ , for the emission of any kind of  $m$  photons is the Poisson distribution function<sup>1</sup>

$$W_m = \frac{\langle m \rangle^m e^{-\langle m \rangle}}{m!}, \quad (8)$$

where  $\langle m \rangle$ , the average multiplicity of emitted photons, was found to be<sup>1</sup>

$$\langle m \rangle = \int dt \Gamma(t) = T\Gamma, \quad (9)$$

with  $T$  formally being the interaction time. If we compare equation (9) with equation (6), we get  $T = \infty$ . On the microscopic level,  $T = \infty$  is all right since, formally, an electron is free only in the infinite past and future. In equation (9), however,  $T$  is to be considered as a macroscopic time, that is, the time needed for an electron to pass through the macroscopic interaction region of finite length  $L$ . If the velocity of an electron while passing through is  $v$ , then

$$T = \frac{L}{v}, \quad (10)$$

giving

$$\langle m \rangle = \frac{L}{v} \Gamma. \quad (11)$$

Once we have arrived at the decay rate,  $\Gamma$ , we can easily evaluate other quantities of interest to the experimentalist. For example, the power spectrum,  $P(\omega)$ , is connected with  $\Gamma$  through the relation<sup>1, 4</sup>

$$\Gamma = \int d\omega \frac{P(\omega)}{\omega}. \quad (12)$$

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, *Phys. Rev. D*, **6** (1978), 2140.

<sup>4</sup>J. Schwinger, Wu-Yang Tsai, and T. Erber, *Classical and Quantum Theory of Synergic Synchrotron-Cerenkov Radiation*, *Ann. Phys.*, **96** (1976), 303.



In this report, we find it convenient to use the following notation for  $P(\omega)$ :

$$P(\omega) \equiv \omega \frac{d\Gamma}{d\omega}, \quad (13)$$

which we defined in analogy to the differential cross section in two-body scattering. Basically, what equation (13) says is that, if  $\Gamma$  is given as an integral over  $\omega$ , then to get  $\omega d\Gamma/d\omega$ , we skip integrating over  $\omega$  and multiply the integrand by  $\omega$ . In fact, this notation for  $P(\omega)$  becomes more transparent if we put equation (13) into equation (12), giving

$$\Gamma = \int d\omega \frac{1}{\omega} \left( \omega \frac{d\Gamma}{d\omega} \right). \quad (12')$$

Equation (12') immediately suggests defining the radiated power in a given solid angle,  $\omega d\Gamma/d\Omega$ , through

$$\begin{aligned} \Gamma &= \int d\Omega \frac{1}{\omega} \left( \omega \frac{d\Gamma}{d\Omega} \right) \\ &= \int d\phi \, d \cos \theta \frac{1}{\omega} \left( \omega \frac{d\Gamma}{d\phi \, d \cos \theta} \right). \end{aligned} \quad (14)$$

If we are not interested in  $\phi$  dependence of the radiated power, we can integrate over  $\phi$ , giving

$$\omega \frac{d\Gamma}{d \cos \theta} = \int_0^{2\pi} d\phi \, \omega \frac{d\Gamma}{d\phi \, d \cos \theta}. \quad (15)$$

On the formal level, we could write, in analogy to equation (14),

$$\Gamma = \int d \cos \theta \frac{1}{\omega} \left( \omega \frac{d\Gamma}{d \cos \theta} \right). \quad (16)$$

Equation (16) is obtained from equation (14) if integration over  $\phi$  is carried out and the remaining integrand is called  $\omega d\Gamma/d \cos \theta$ .

Experimentally, we are interested also in the emitted number of photons within a frequency region  $\omega_1$  to  $\omega_2$ :<sup>1</sup>

$$\langle m \rangle_{\omega_1, \omega_2} = \frac{L}{v} \Gamma_{\omega_1, \omega_2} \quad , \quad (17)$$

where

$$\Gamma_{\omega_1, \omega_2} = \int_{\omega_1}^{\omega_2} d\omega \frac{d\Gamma}{d\omega} \quad . \quad (18)$$

The number of photons in the frequency interval from  $\omega$  to  $\omega + d\omega$  is

$$\langle m \rangle_{\omega, \omega+d\omega} = \frac{d\langle m \rangle}{d\omega} d\omega \quad , \quad (19)$$

where the number of photons per unit frequency is

$$\frac{d\langle m \rangle}{d\omega} = \frac{L}{v} \frac{d\Gamma}{d\omega} = \frac{L}{v} \frac{1}{\omega} \left( \omega \frac{d\Gamma}{d\omega} \right) \quad . \quad (20)$$

If we know  $\omega$  and  $\omega d\Gamma/d\omega$  as functions of  $\cos \theta$ , then we know also  $d\langle m \rangle/d\omega$  as a function of  $\cos \theta$ .

Using equations (11) and (14), we can also calculate the number of photons of any frequency in a given solid angle. The result after integrating over  $\phi$  is

$$\frac{d\langle m \rangle}{d \cos \theta} = \frac{L}{v} \frac{d\Gamma}{d \cos \theta} = \frac{L}{v} \frac{1}{\omega} \left( \omega \frac{d\Gamma}{d \cos \theta} \right) \quad . \quad (21)$$

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<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, *Phys. Rev. D*, 6 (1978), 2140.



### 3. SPECIFIC EXPRESSIONS

In this section, we give specific expressions for some quantities discussed in section 2 for the stimulated radiation resulting from the interaction between an electron beam and an incident electromagnetic wave, as schematically shown in figure 1.

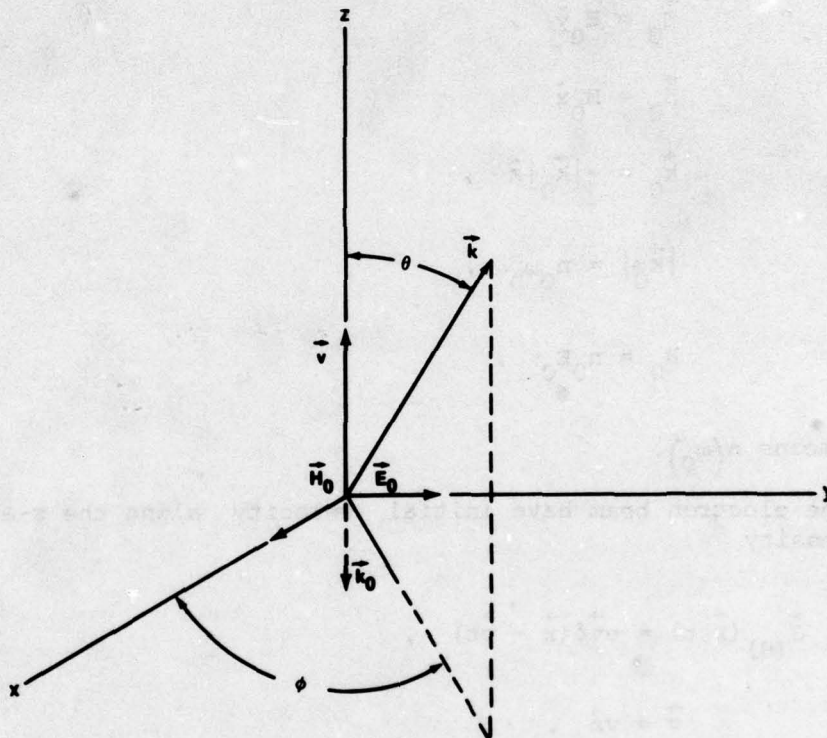


Figure 1. Schematic of head-on electron-electromagnetic field collision for stimulated electron radiation. Velocity  $\vec{v}$  of incident electron and wave vector  $\vec{k}_0$  of sinusoidal electromagnetic field are antiparallel and chosen to be along z-axis. Constant electric  $\vec{E}_0$  and magnetic  $\vec{H}_0$  fields define polarization of electromagnetic field. Momentum of radiated photon is denoted by  $\vec{k}$ , whose direction is defined by angles  $\theta$  and  $\phi$ .

For a medium at rest, we take the incident electromagnetic field to be<sup>1, 5-7</sup>

$$\vec{E}(\vec{x}, t) = \vec{E}_0 \sin(\omega_0 t - \vec{k}_0 \vec{x}) ,$$

$$\vec{H}(\vec{x}, t) = \vec{H}_0 \sin(\omega_0 t - \vec{k}_0 \vec{x}) ,$$

$$\vec{E}_0 = E_0 \hat{y} ,$$

$$\vec{H}_0 = H_0 \hat{x} ,$$

$$\vec{k}_0 = -|\vec{k}_0| \hat{z} ,$$

$$|\vec{k}_0| = n_0 \omega_0 ,$$

$$H_0 = n_0 E_0 , \quad (22)$$

where  $n_0$  means  $n(\omega_0)$ .

Let the electron beam have initial velocity along the z-axis, with current density

$$\vec{J}_{(0)}(\vec{x}, t) = e \vec{v} \delta(\vec{x} - \vec{v} t) ,$$

$$\vec{v} = v \hat{z} . \quad (23)$$

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, Phys. Rev. D, 6 (1978), 2140.

<sup>5</sup>S. Schneider and R. Spitzer, *Interaction of Coherent Electromagnetic Waves with Relativistic Electrons in a Medium*, Nature, 250 (1974), 643.

<sup>6</sup>S. Schneider and R. Spitzer, *Stimulated Electromagnetic Shock Radiation*, Second International Conference and Winter School on Submillimeter Waves and Their Applications (1976), 132.

<sup>7</sup>S. Schneider and R. Spitzer, *Application of Stimulated Electromagnetic Shock Radiation (SESR) to the Generation of Intense Submillimeter and Far Infrared Waves*, Second International Conference and Winter School on Submillimeter Waves and Their Applications (1976), 134.



Because of the interaction, this current density is changed into

$$\vec{J}(\vec{x}, t) = e\vec{V}(t)\delta[\vec{x} - \vec{R}(t)] ,$$

$$\vec{R}(t) = \vec{v}t + \vec{r}(t) ,$$

$$\vec{V}(t) = \dot{\vec{R}}(t) = \vec{v} + \dot{\vec{r}}(t) , \quad (24)$$

where  $\vec{r}(t)$  is the change in the trajectory of the electron. Working in the approximation

$$|\vec{r}(t)| \approx 0(e) , \quad (25)$$

one can determine  $\vec{r}(t)$  from the Lorentz force equation to be<sup>1</sup>

$$\vec{r}(t) = \frac{e\vec{E}_0(1 + v n_0)}{m \gamma_0} \lim_{\mu \rightarrow 0} \int dt' D_R(t - t'; \mu) \sin \omega_0 t' (1 + v n_0) ,$$

$$\gamma_0^2 = \frac{1}{1 - v^2} , \quad (26)$$

where  $D_R$  was derived to be<sup>1</sup>

$$D_R(t; \mu) = \theta(t) \frac{\sin \mu t}{\mu} = \frac{1}{2\pi} \int d\omega \frac{e^{-i\omega t}}{\mu^2 - (\omega + i\epsilon)^2} , \quad \epsilon \rightarrow +0 ,$$

$$\theta(t) = \begin{cases} 1, & t > 0 , \\ 0, & t < 0 . \end{cases} \quad (27)$$

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, Phys. Rev. D, 6 (1978), 2140.

With this we can write the current density from equation (24) as<sup>4</sup>

$$\begin{aligned}\vec{J}(\vec{x}, t) &= \vec{J}_{(0)}(\vec{x}, t) + \vec{J}_s(\vec{x}, t) , \\ \vec{J}_s(\vec{x}, t) &= \vec{J}_{(1)}(\vec{x}, t) + \vec{J}_{(2)}(\vec{x}, t) ,\end{aligned}\quad (28)$$

where  $\vec{J}_{(0)}$  is given by equation (23) and, to  $O(e^2)$ ,

$$\begin{aligned}J_{(1)}^i(\vec{x}, t) &= e\dot{r}^i(t)\delta(\vec{x} - \vec{v}t) , \\ J_{(2)}^i(\vec{x}, t) &= -ev^i[\vec{r}(t)\nabla(x)]\delta(\vec{x} - \vec{v}t) .\end{aligned}\quad (29)$$

The Fourier transforms of equation (29) are easily found<sup>1</sup> to be ( $k^4 = \omega$ ),

$$\begin{aligned}J_{(1)}^i(\vec{k}, \omega) &= -\frac{e^2\pi E_0^i}{\gamma_0 m\omega_0} \left\{ \delta[\omega - \vec{k}\vec{v} + \omega_0(1 + v n_0)] \right. \\ &\quad \left. + \delta[\omega - \vec{k}\vec{v} - \omega_0(1 + v n_0)] \right\} , \\ J_{(2)}^i(\vec{k}, \omega) &= \frac{e^2\pi E_0 k_2 v^i}{\gamma_0 m\omega_0^2(1 + v n_0)} \left\{ \delta[\omega - \vec{k}\vec{v} + \omega_0(1 + v n_0)] \right. \\ &\quad \left. - \delta[\omega - \vec{k}\vec{v} - \omega_0(1 + v n_0)] \right\} , \\ J_s^i(\vec{k}, \omega) &= J_{(1)}^i(\vec{k}, \omega) + J_{(2)}^i(\vec{k}, \omega) .\end{aligned}\quad (30)$$

The  $J_s^i(\vec{x}, t)$  or, equivalently,  $J_s^i(\vec{k}, \omega)$ , are responsible for the stimulated radiation that we are interested in. We get the decay rate,  $\Gamma$ , for the stimulated radiation by combining equations (3), (7), and (30). The result is

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, *Phys. Rev. D*, **6** (1978), 2140.

<sup>4</sup>J. Schwinger, Wu-Yang Tsai, and T. Erber, *Classical and Quantum Theory of Synergic Synchrotron-Cerenkov Radiation*, *Ann. Phys.*, **96** (1976), 303.



$$\begin{aligned}
\Gamma = & \frac{\alpha^2 E_0^2}{2m^2 \gamma_0^2 v \omega_0^2} \int d\omega \, d\phi \, d \cos \theta \left\{ \left[ (1 - \sin^2 \theta \sin^2 \phi) \right. \right. \\
& + \left. \left( \frac{\omega}{\omega_0} \right)^2 \frac{a^2 \sin^4 \theta \sin^2 \phi}{(1 + a_0)^2} \right] \left[ \delta \left( \cos \theta - \frac{1}{a} - \frac{\omega_0 (1 + a_0)}{\omega a} \right) \right. \\
& + \left. \left. \delta \left( \cos \theta - \frac{1}{a} + \frac{\omega_0 (1 + a_0)}{\omega a} \right) \right] \right. \\
& + \left. \left( \frac{\omega}{\omega_0} \right) \frac{2a \sin^2 \theta \cos \theta \sin^2 \phi}{1 + a_0} \left[ \delta \left( \cos \theta - \frac{1}{a} - \frac{\omega_0 (1 + a_0)}{\omega a} \right) \right. \right. \\
& - \left. \left. \delta \left( \cos \theta - \frac{1}{a} + \frac{\omega_0 (1 + a_0)}{\omega a} \right) \right] \right\}, \tag{31}
\end{aligned}$$

where the notations

$$a = nv$$

and

$$a_0 = n_0 v$$

are used.

In equation (31), the  $\delta$ -functions basically define the kinematics of the stimulated radiation.

In what follows, we assume that  $n$  may be a function of frequency only, that is, that we have an isotropic medium. Then the  $\delta$ -functions imply that the stimulated radiation can occur at a fixed angle,  $\theta$ . Furthermore, the stimulated radiation is assumed to occur in the vacuum (0) branch if

$$a < 1; \tag{33a}$$

in the forward (+) Cerenkov branch if

$$a > 1$$

and

$$a \cos \theta > 1 ;$$

and in the backward (-) Cerenkov branch if

$$a > 1$$

and

$$a \cos \theta < 1 .$$

The two Cerenkov branches meet at angle  $\bar{\theta}$ , where the usual (spontaneous) Cerenkov radiation occurs,

$$a \cos \bar{\theta} = 1 . \quad (34)$$

However, at angle  $\bar{\theta}$ , we should not have stimulated radiation as the  $\delta$ -functions imply. As a consequence, we do not expect to observe those frequencies in stimulated radiation for which equation (34) can be satisfied (which frequencies may involve more than one angle  $\bar{\theta}$ ).<sup>1</sup>

From  $\delta$ -functions appearing in equation (31), we can relate the frequency upshift,  $\omega/\omega_0$ , and  $\cos \theta$  for each of the branches:

$$\text{for } (0): \quad \frac{\omega}{\omega_0} = \frac{1 + a_0}{1 - a \cos \theta} , \quad (35a)$$

$$\text{for } (+): \quad \frac{\omega}{\omega_0} = \frac{1 + a_0}{a \cos \theta - 1} , \quad (35b)$$

$$\text{for } (-): \quad \frac{\omega}{\omega_0} = \frac{1 + a_0}{1 - a \cos \theta} . \quad (35c)$$

From equations (33) and (35), we can read off  $\omega/\omega_0$  only when  $n$  is assumed to be independent of  $\omega$ .

<sup>1</sup>J. Soln, *Differential Equations with Respect to a Coupling Constant: An Approach to Cerenkov and Stimulated Radiations*, Phys. Rev. D, 6 (1978), 2140.



If we integrate over  $\omega$  and  $\phi$  in equation (31), then equation (16) immediately tells us the radiated power as a function of  $\cos \theta$ . Furthermore, let us assume that  $a < 1$  (vacuum branch) so that only one  $\delta$ -function in equation (31) contributes to  $\Gamma$ . The result is

$$\frac{\omega d\Gamma}{d \cos \theta} = F \frac{\pi n (1 + a_0)^2}{\gamma_0^2 |a \cos \theta - 1|} \left[ \frac{1 + \cos^2 \theta}{(1 - a \cos \theta)^2} - \frac{2a \sin^2 \theta \cos \theta}{(1 - a \cos \theta)^3} + \frac{a^2 \sin^4 \theta}{(1 - a \cos \theta)^4} \right],$$

$$F = \frac{\alpha^2 E_0^2}{2m^2} \quad (36)$$

Although equation (36) was derived for the vacuum (0) branch (eq (33a)), it can be easily shown to be valid for the forward (+) and backward (-) Cerenkov branches (eq (33b), (33c)). The important thing to note is that we assumed  $n$  to be very weakly dependent on  $\omega$  so that, for practical purposes,  $n$  is the same for all  $\omega$ 's of interest.

In a similar manner, using equations (12'), (20), and (31), we get, for the number of photons per unit frequency as a function of  $\cos \theta$ ,

$$\frac{d\langle m \rangle}{d\omega} = G \frac{\pi}{\gamma_0^2 v^2 a^2} \left[ (1 + a^2) + \frac{2(a^2 - 1)}{1 - a \cos \theta} + \frac{(1 - a^2)^2}{(1 - a \cos \theta)^2} \right], \quad (37a)$$

$$G = \frac{L \alpha^2 E_0^2}{2m \omega_0^2} = \frac{L}{\omega_0^2} F, \quad (37b)$$

where  $L$  is the interaction length (see eq (10), (11)). Equations (37) are valid separately for all three branches: the vacuum (0) branch (eq (33a), (35a)), the forward (+) Cerenkov branch (eq (33b), (35b)), and the backward (-) Cerenkov branch (eq (33c), (35c)). Although  $n$  ( $a = nv$ ) in equations (37) may depend arbitrarily on  $\omega$ , we assume that for  $\omega$ 's of interest it is actually weakly dependent on  $\omega$ . Otherwise, the  $\theta$ -dependence would be more involved than indicated by equations (37) (see eq (35)).

The power spectrum as defined by equation (12) or (12') can be derived in a similar manner. Unfortunately, for each of the branches, the expression is different, and, since these expressions are given in reference 1, we do not repeat them here.

We end this section by evaluating total radiated powers (W) for each of the branches:

$$\begin{aligned} W^{(0)} &= \int_1^0 d \cos \theta \left( \frac{\omega d\Gamma}{d \cos \theta} \right) \\ &= F \frac{8\pi n (1 + a_0)^2}{3(1 - a^2)^2} \end{aligned} \quad (38a)$$

for the vacuum (0) branch,

$$W^{(+)} = \int_{\cos \bar{\theta}}^1 d \cos \theta \left( \frac{\omega d\Gamma}{d \cos \theta} \right) \rightarrow \infty \quad (38b)$$

for the forward (+) Cerenkov branch, and

$$W^{(-)} = \int_1^{\cos \bar{\theta}} d \cos \theta \left( \frac{\omega d\Gamma}{d \cos \theta} \right) \rightarrow \infty \quad (38c)$$

for the backward (-) Cerenkov branch. That  $W^{(+)}$  and  $W^{(-)}$  are divergent we attribute, to a lesser extent, to ignoring the dispersion and, to a larger extent, to neglecting the recoil of the electron, which can be significant for large  $\omega$ 's. We believe that, by just including the recoil of the electron into the theory, we would get finite expressions for  $W^{(+)}$  and  $W^{(-)}$ .

Inspecting equation (38a) for  $W^{(0)}$ , we conclude that already in the vacuum branch the stimulated radiation can be efficient if  $a$  ( $<1$ ) can be very close to 1. This high efficiency could be achieved already with low-energy electrons (about 1 MeV) if the index of refraction could be maintained at about 1.05.



Although  $W^{(+)}$  and  $W^{(-)}$  diverge, their difference is finite. In fact, one can show with little work that the following sum rule holds:

$$W^{(-)} - W^{(+)} = W^{(0)} \Big|_{a \rightarrow a > 1}, \quad (39)$$

where  $a \rightarrow a > 1$  means that  $W^{(0)}$  from equation (38a) is analytically continued from  $a < 1$  to  $a > 1$ . Since  $W^{(0)}$  is known explicitly as a function of  $a$ , equation (39) could be quite useful in experimentally relating  $W^{(+)}$  to  $W^{(-)}$  and vice versa.

#### 4. NUMERICAL ANALYSIS, DISCUSSION, AND CONCLUSION

Although the results for total radiated power in Cerenkov branches diverge and cannot directly render physically reliable values, the sum rule (eq (39)) can nevertheless be accepted as physically reliable. Namely, it is reasonable to assume that the inclusion of dispersion and the recoil of the electron into the theory would have the effect of changing  $\cos \bar{\theta}$  as

$$\cos \bar{\theta} \rightarrow \cos \bar{\theta} + \epsilon(+), \quad \epsilon(+)>0, \quad (40)$$

in equation (38b), and

$$\cos \bar{\theta} \rightarrow \cos \bar{\theta} - \epsilon(-), \quad \epsilon(-)>0, \quad (41)$$

in equation (38c). We expect  $\epsilon(+)$  and  $\epsilon(-)$  to be small. It can be shown easily that  $\epsilon(+)$  and  $\epsilon(-)$  are related in such a way that  $W^{(+)}$  and  $W^{(-)}$  become finite, still satisfying the sum rule (eq (39)). Unfortunately, this argument still leaves one of them undetermined--say,  $\epsilon(+)$ --and proves our assertion that we need, for example, the recoil of the electron in the theory to determine  $W^{(+)}$  and  $W^{(-)}$  completely. However, since substitution equations (40) and (41) effectively eliminate very high  $\omega$ 's and since the recoil of the electron is expected to have effect only on high values of  $\omega$ , it stands to reason that the sum rule (eq (39)) is generally valid. With this validity in mind, we conclude that, in view of equation (39), the stimulated radiations could be made even more efficient in the Cerenkov branches than in the vacuum branch.

Here, we give an example of calculated efficiency for the vacuum branch. If  $E_K$  denotes the kinetic energy of the electron and  $T$  the interaction time (compare with eq (10)), then the efficiency,  $R^{(0)}$ , in the vacuum branch is

$$R^{(0)} = \frac{LW^{(0)}}{vE_K} \quad (42)$$

Take

$$E_K \approx 1.165 \text{ MeV } (\gamma_0 \approx 3.28),$$

$$n = n_0 = 1.05,$$

$$L = 10 \text{ cm},$$

$$E_0 = 6.5 \text{ statvolt/cm}, \quad (43)$$

where  $E_0$  in equation (43) corresponds to the peak electric field of the traveling microwave pump. The factor  $F$  (compare with eq (36)) appearing in  $W^{(0)}$  is given in the natural system of units. To express it in cgs units, we note that

$$\begin{aligned} F &= \left( \frac{e^2}{4\pi} \right)^2 \frac{E_0^2}{2m^2} = \left( \frac{e^2}{4\pi\hbar c} \right)^2 \frac{\hbar^2 E_0^2 c^2}{2m^2} \\ &= \left( \frac{e^2}{4\pi\hbar c} \right)^2 \frac{\hbar^2 (4\pi c E_0^2)}{8\pi \left( \frac{m}{c} \right)^2 c} \end{aligned} \quad (44)$$

Now we identify  $e^2/4\pi\hbar c$  with fine structure constant  $\alpha$ ,  $(4\pi c)^{1/2} E_0$  with  $E_0$ , and  $m/c$  with  $m$  in cgs units, respectively. Thus,

$$F = \frac{\alpha^2 \hbar^2 E_0^2}{8\pi m^2 c} \quad (45)$$

where now all quantities in equation (45) are to be expressed in cgs units, and

$$\alpha \approx \frac{1}{137} \quad (46)$$

It is not difficult to check that  $F$  in equation (45) has indeed the dimension of power. Taking into account that  $1 \text{ MeV} \approx 1.6 \times 10^{-6} \text{ erg}$ , the efficiency for equation (42) turns out to be

$$R^{(0)} \approx 0.03 \text{ percent} \quad (47)$$



This is actually a rather impressive result if we take into account the fact that the interaction length is only 10 cm and that the microwave pump has a weak electric field. However, just increasing  $L$  and  $E$  each by a factor of 10 increases the efficiency by a factor of  $10^3$ , that is, to about 30 percent.

The difference between vacuum and Cerenkov branches in stimulated electron radiation can be seen in figures 2 to 19. There, frequency upshifts (fig. 2 to 7), radiated powers (fig. 8 to 13), and mean numbers of photons per unit frequency (fig. 14 to 19) are plotted versus  $\cos \theta$  for indices of refraction ( $n$ ) of 1.000, 1.005, 1.01, 1.02, 1.05, and 1.10 and electron velocities of 0.9, 0.95, and 0.99. In all these figures, the Cerenkov branches already develop at  $n = 1.02$  and  $v = 0.99$  ( $a = nv > 1$ .) All these quantities exhibit singularities at  $\theta = \bar{\theta}$ . These singularities presumably will be removed once the recoil of the electron is incorporated (quantum theory of stimulated electron radiation). Nevertheless, from these figures, we conclude that the stimulated radiation should be very efficient at angles  $\theta$  close to  $\bar{\theta}$  when the process is going through a Cerenkov branch, provided that the index of refraction is only weakly dependent on  $\omega$ . The radiated power and the mean number of photons per unit frequency are plotted as dimensionless quantities by being divided by  $F$  (eq (36)) and  $G$  (eq (37)), respectively. For convenience, we have assumed that  $n = n_0$  throughout the figure captions.

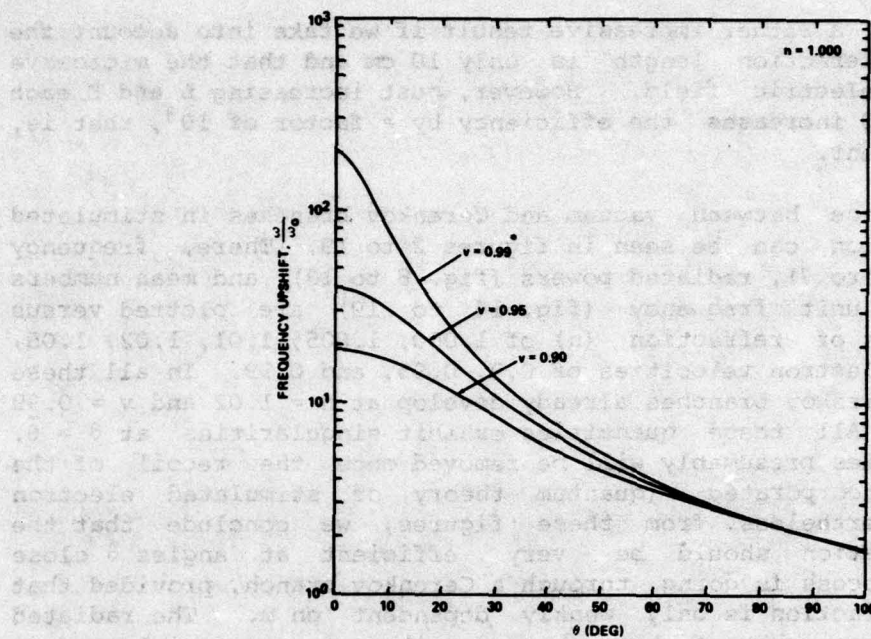


Figure 2. Frequency upshift versus  $\cos \theta$ ; frequency upshift is largest at  $\theta = 0$ .

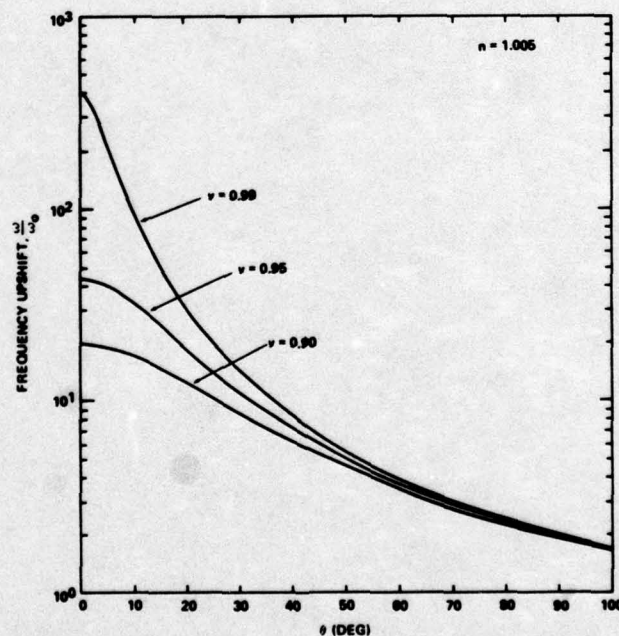


Figure 3. Frequency upshift versus  $\cos \theta$ .



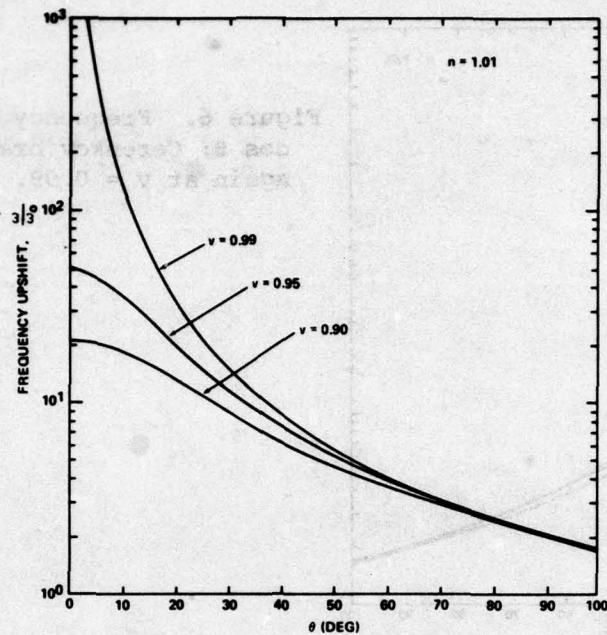


Figure 4. Frequency upshift versus  $\cos \theta$ ;  $\omega/\omega_0$  increases dramatically for small  $\theta$ .

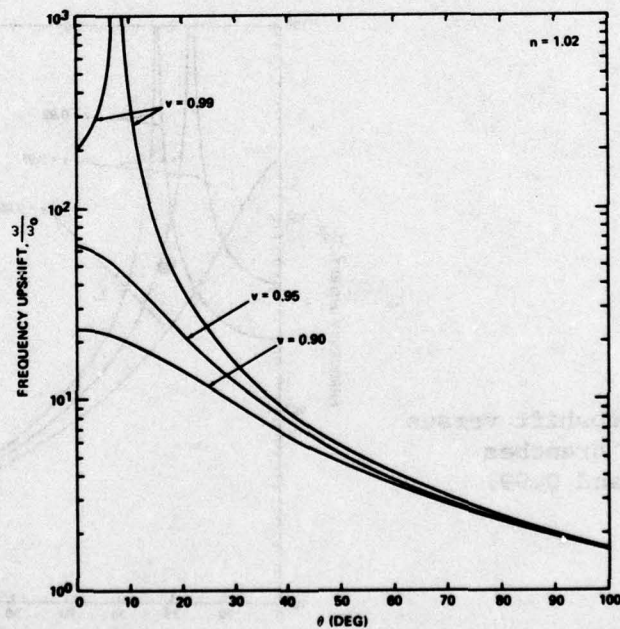


Figure 5. Frequency upshift versus  $\cos \theta$ ; forward and backward Cerenkov branches develop for  $v = 0.99$ , where  $\omega/\omega_0$  can be made very large.

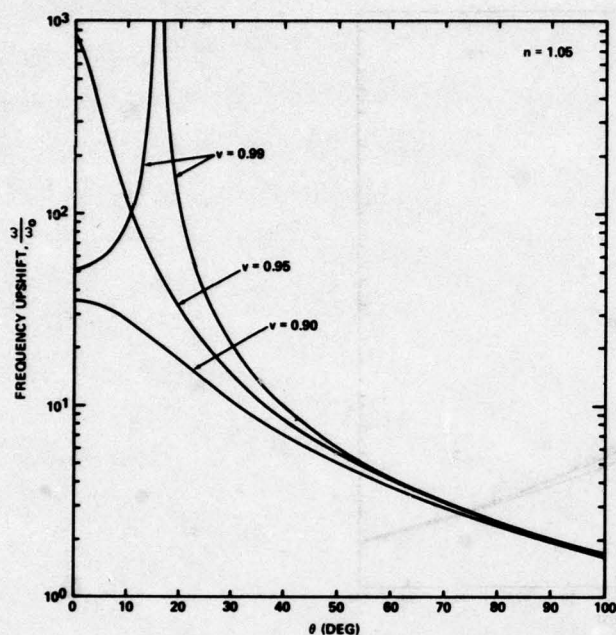


Figure 6. Frequency upshift versus  $\cos \theta$ ; Cerenkov branches appear again at  $v = 0.99$ .

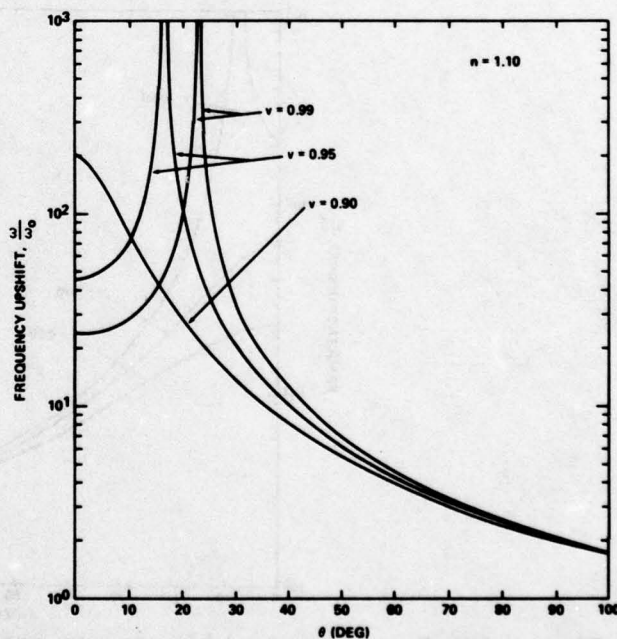


Figure 7. Frequency upshift versus  $\cos \theta$ ; two Cerenkov branches appear at  $v = 0.95$  and  $0.99$ .



Figure 8. Radiated power versus  $\cos \theta$ ; small angles are favored by radiated power.

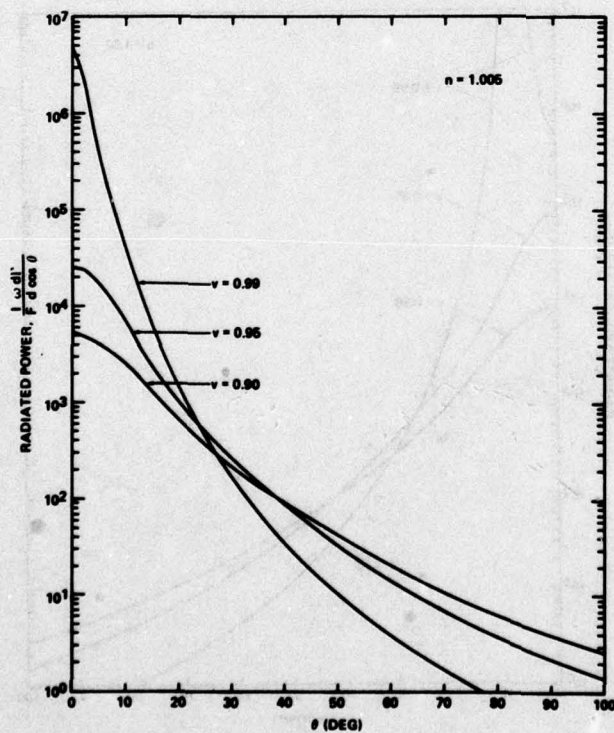
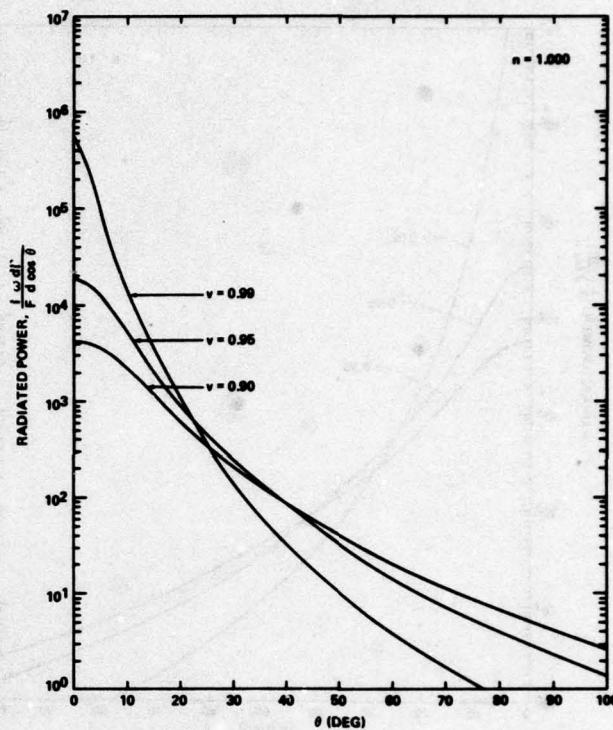


Figure 9. Radiated power versus  $\cos \theta$ .

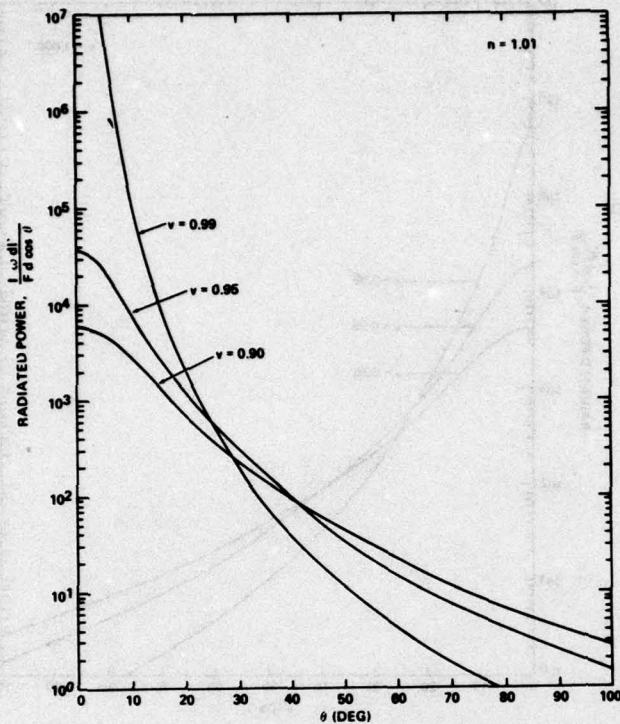


Figure 10. Radiated power versus  $\cos \theta$ ; radiated power increases dramatically for small  $\theta$ .

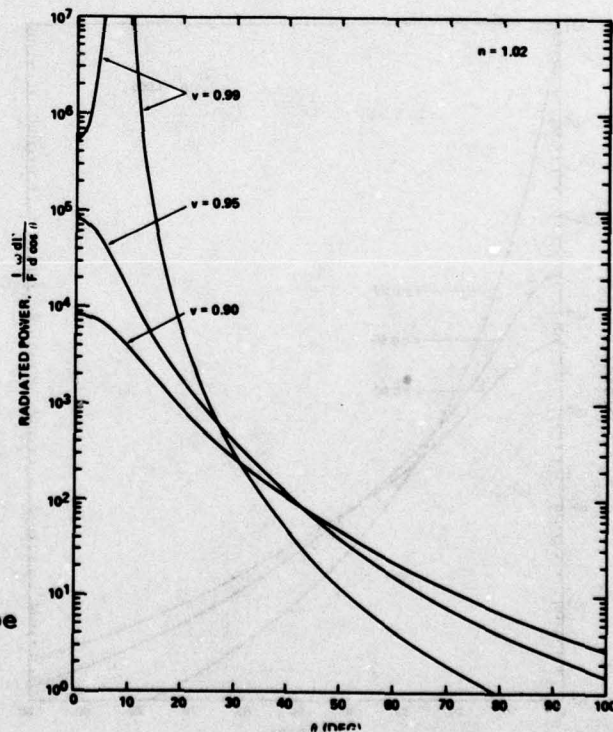


Figure 11. Radiated power versus  $\cos \theta$ ; forward and backward Cerenkov branches appear at  $v = 0.99$ , where radiated power can be made very large.



Figure 12. Radiated power versus  $\cos \theta$ ; Cerenkov branches appear again at  $v = 0.99$ .

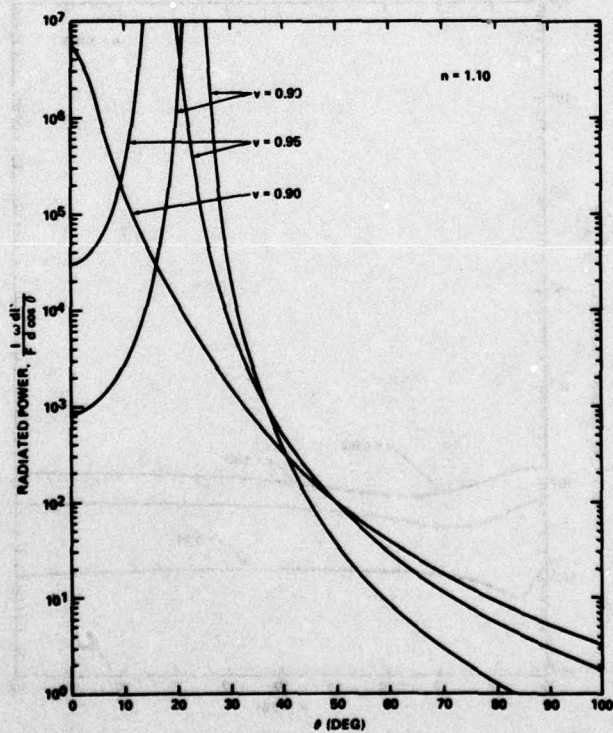
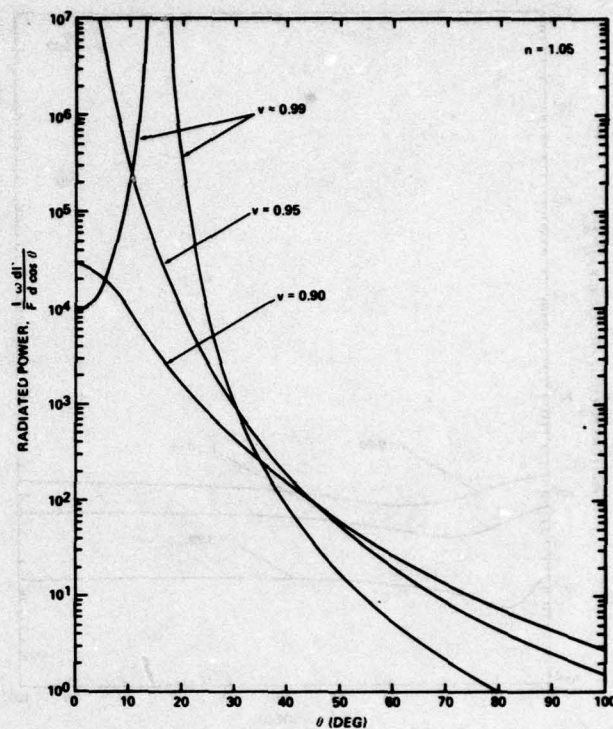


Figure 13. Radiated power versus  $\cos \theta$ ; two Cerenkov branches appear at  $v = 0.95$  and  $0.99$ .

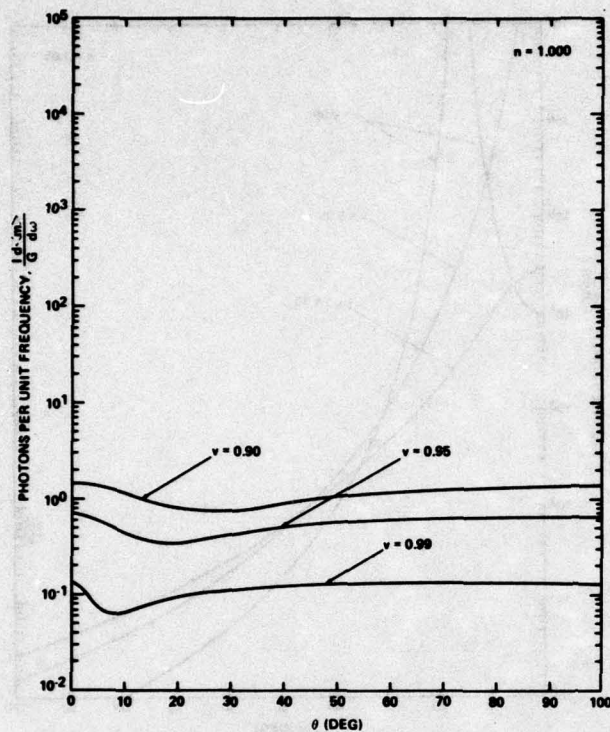


Figure 14. Mean number of photons per unit frequency versus  $\cos \theta$ ; curves are smooth for all  $\theta$ .

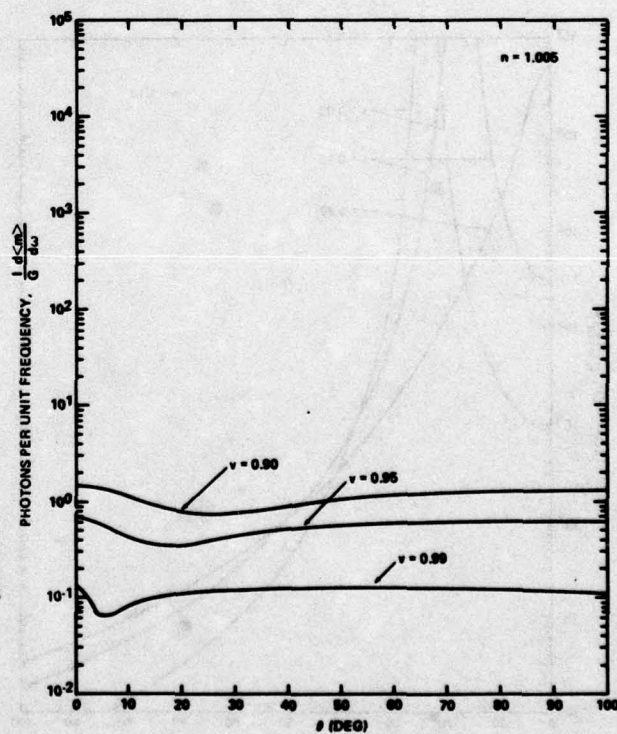


Figure 15. Mean number of photons per unit frequency versus  $\cos \theta$ .



Figure 16. Mean number of photons per unit frequency versus  $\cos \theta$ .

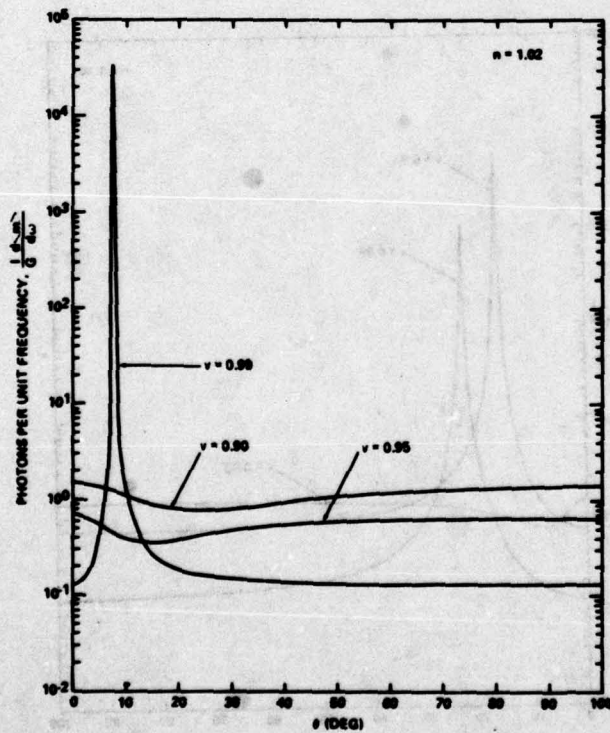
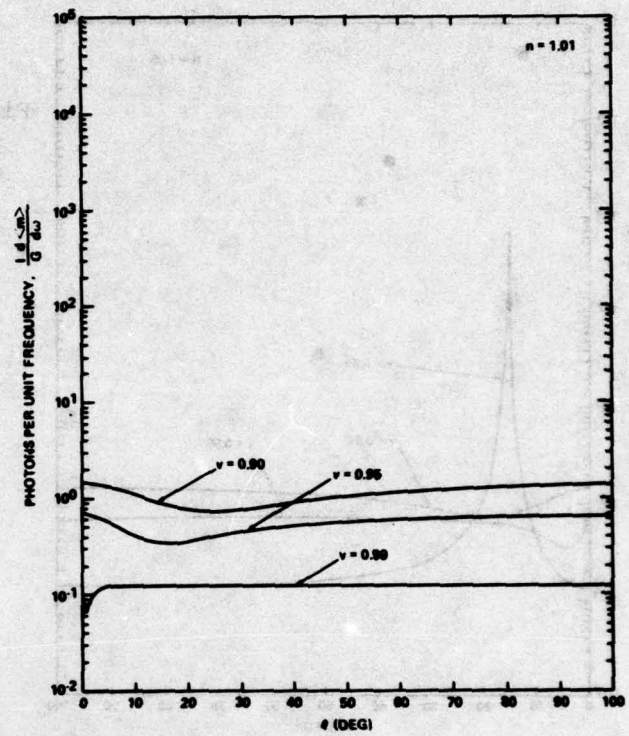


Figure 17. Mean number of photons per unit frequency versus  $\cos \theta$ ; Cerenkov branches appear at  $v = 0.99$ .

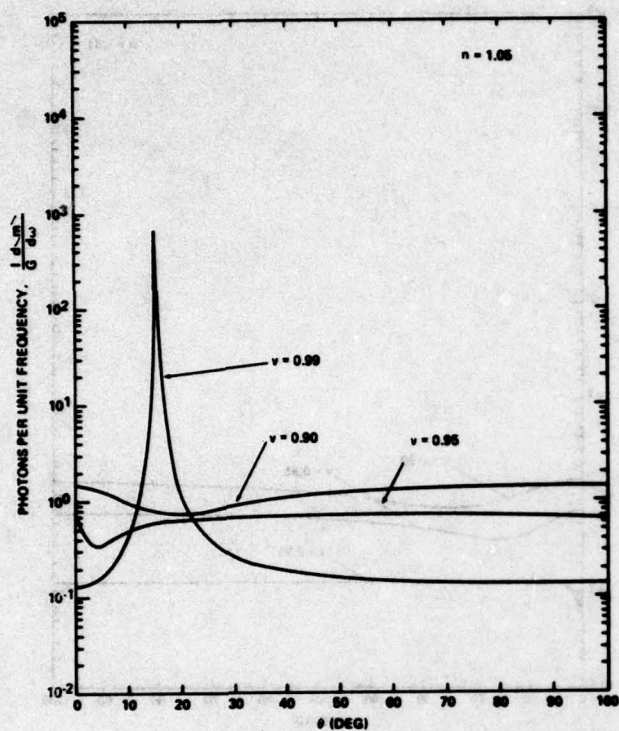


Figure 18. Mean number of photons per unit frequency versus  $\cos \theta$ ; Cerenkov branches appear again at  $v = 0.99$ .

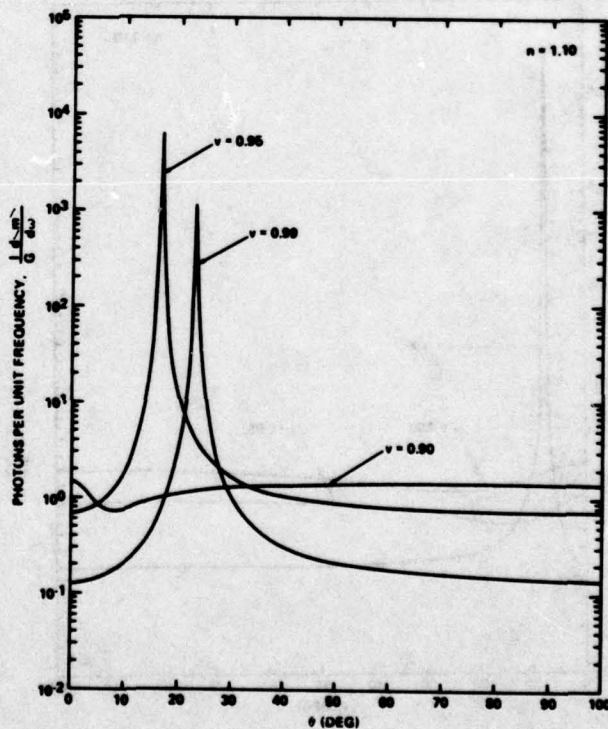


Figure 19. Mean number of photons per unit frequency versus  $\cos \theta$ ; two Cerenkov branches appear at  $v = 0.95$  and  $0.99$ , where mean number of photons per unit frequency could be made very large.



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